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Transient Stability Improvement: A Review and Comparison of Conventional and Renewable based Techniques for Preventive and Emergency Control

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Abstract This paper aims at reviewing and summarizing the vast variety of techniques to improve transient stability of power systems. A qualitative comparison of the techniques is presented and the future outlook is discussed. The techniques are categorized into conventional and renewable-based techniques. Conventional techniques are well established and have been employed in the past. Renewable techniques investigate how generators based on renewable energy sources (RES) can contribute to improving stability. Moreover, it is distinguished between techniques applying preventive and emergency controls. For preventive control, re-dispatch of generators and series compensation are extensively used in practice, whereas for emergency control, a great share of the techniques aim at voltage support during fault conditions. Regarding preventive control using RES-based generation, one approach which temporarily increases the voltage setpoint of the units in order to increase the synchronizing power, is reported. Regarding renewable energy source based emergency control, low voltage ride-through (LVRT) capability including voltage support is a well established method. Nevertheless, it is also highlighted that high voltage ride-through (HVRT) capability plays a critical role. The findings show that distributed generation must be included in existing control schemes for preventive control, and new improvement techniques taking full advantage of them need to be developed.

Keywords Transient Stability Improvement · Power System Stability · Preventive Control · Emergency Control · Renewable Energy Sources

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1 Introduction

The generation of electric power is currently shifting from large centralized to small distributed generation units [1]. The continuing integration of renewable energy sources (RES) also changes the characteristics of the power systems due to their different behavior compared to conventional synchronous generators (SG) [2]. Therefore, great effort in research is put into investigating different aspects on how RES, such as wind and photovoltaics (PV), are affecting the stability of power systems. A particularly important property of power systems is their transient rotor angle stability, which is the ability of the generators to remain in synchronism after a large disturbance [3]. Synchronism means that all SGs in a power system are running at the same speed. On the contrary, converter-based generation units are not rotating machines and thus do not have a rotor angle but they are synchronized to the connected grid through a phase-locked loop (PLL) [4–6]. Such a disturbance can lead to widespread outages due to unintended and/or uncoordinated tripping of protection devices. Here, large disturbance does not necessarily need to refer to a fault, since an instability can also be triggered by tripping of a heavily loaded line or generator [7].

Anticipating a future scenario with high share of converter-based generation, the approaches to maintain or re-establish transient stability have to change since converters have other properties and capabilities than conventional SGs [8]. Converter-based generation units do not inherently provide inertia to the grid, unless they are equipped with an explicit control to do so. Moreover, a great share of wind power plants include asynchronous generators which do provide inertia to the system, but their contribution is small compared to SGs [9]. That means, the dynamic behavior of the whole power system continuously changes in course of time, depending on the actual energy mix of synchronous and converter-based generation, which may compromise transient stability in certain situations and, thus, the reliability [10]. Therefore it is important to develop new techniques for transient stability preventive and emergency control, also taking into account asynchronous and converter-based generation units to guarantee the reliability of future power systems [11].

This paper intends to summarize the state-of-the-art for transient stability improvement. A categorization in conventional and RES-based techniques is carried out. Within these two categories it is further distinguished between preventive and emergency control. Finally, the techniques are qualitatively compared and a future outlook is presented. The paper is organized as follows. In section 2, the basics of transient stability assessment and improvement are revisited. Conventional improvement techniques are described in section 3. Improvement techniques using RES are described in section 4. The qualitative aspects of the techniques are discussed in section 5. The conclusion and future outlook are given in section 6 where the most important improvement techniques are summarized and future research needs are highlighted.

2 Basics of Transient Stability Assessment and Improvement

2.1 Nomenclature

$P_{e,pre}$ (W) - Active power transfer capability <u>before</u> the fault.
$P_{e,f}$ (W) - Active power transfer capability <u>during</u> the fault.
$P_{e,post}$ (W) - Active power transfer capability <u>after</u> the fault.
P_m (W) - Mechanical power supplied to the turbine.
P_a (W) - Acceleration/deceleration power defined as difference between mechanical and electrical power.
J (kgm^2) - Moment of inertia.
δ_0 (rad) - Steady-state rotor angle before the fault.
δ_1 (rad) - Steady-state rotor angle after the fault.
δ_c (rad) - Critical rotor angle which defines stability limit during fault.
δ_m (rad) - Maximum permissible rotor angle perturbation after fault clearance.
A_1, A_2 - Acceleration and deceleration areas.

2.2 Transient Stability Mechanism

In order to understand the different effects of the improvement techniques, the basics of transient stability assessment are briefly summarized by means of the well-known equal area criterion (EAC) [12,13].

The EAC determines the transient stability limit according to the acceleration and deceleration area A_1 and A_2, respectively. The corresponding $P - \delta$ diagram is shown in Fig. 1. The physical relation between the mechanical and electrical quantities is given by the equation of motion shown in (1). Generators are accelerating or decelerating once there is a mismatch between mechanical power supplied to the turbine and electrical power delivered to the grid.

$$P_a = P_m - P_e = J\omega_0 \frac{d^2\delta}{dt^2} \tag{1}$$

The stability limit is derived by calculating the maximum clearing angle and, based on that, the critical clearing time (CCT) which describes the time that the generator takes to advance from the initial rotor angle to the critical rotor angle. Hence, the greater the CCT, the more severe disturbances the generator (system) can withstand.

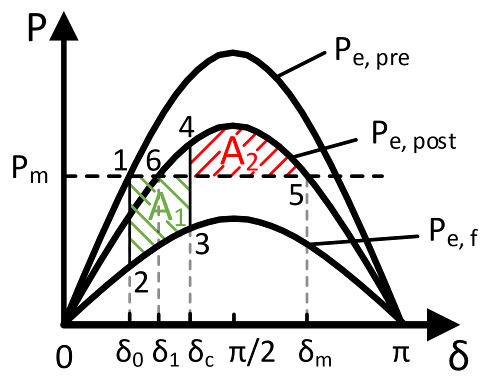


Fig. 1: P-δ curve

2.3 Improvement Mechanisms

Several variables affect the transient stability. Thus, a wide variety of techniques for improvement of power system stability can be found in the literature. All discussed transient stability improvement techniques can be referred to one of the following effects.

On the one hand, improving transient stability can be achieved by reducing the fault severity, e.g. faster fault clearance, or, on the other hand, by increasing the CCT. According to [13], the techniques of transient stability improvement are aiming to achieve one or more of the following effects:

a) Reduction of the impact of the disturbance or the fault severity.
b) Increase of the synchronization forces to support the restoration of steady-state operation after a disturbance.
c) Reduction of the acceleration or deceleration power through control of the prime mover to meet the equilibrium of mechanical and electrical power.
d) Applying artificial load to SG to reduce accelerating power by increasing electrical power.

Effects related to a) can be achieved by faster fault clearing times through high speed breakers and, thus, reduces the fault severity by decreasing the clearing angle. An increase of the synchronization forces mentioned in b) can be realized by the use of Flexible Alternating Current Transmission Systems (FACTS) by e.g. voltage support at a long transmission line. techniques related to c) and d) refer to the re-establishment of the equilibrium between the mechanical and electrical power, thus, reducing the acceleration/deceleration power on the shaft of the synchronous machine.

3 Conventional Techniques

In this section conventional techniques for transient stability improvement are discussed. A technique is considered conventional when no RES are involved. conventional techniques make up the greatest part in the literature since they includes techniques with SGs, FACTS and any other approaches that do not involve RES-based units.

3.1 Preventive Transient Stability Control

3.1.1 SG Re-Dispatch

One of the most effective preventive actions to increase the transient stability margin is to re-dispatch generators in order to reduce their active power setpoint. That means, generators are operated further away from the stability limit. Considering Fig. 1, the acceleration area decreases and the deceleration area increases. Due to cost efficiency, the dispatch of generators is usually determined by the use of optimal power flow (OPF) calculations where either transient stability constraints are derived from a time-domain sensitivity analysis, or the whole set of power flow equations is directly included in the OPF formulation [14–17]. In [14], a 4^{th}-order Taylor expansion is used to speed up solving of OPF calculations including transient stability constraints. The authors of [15] propose to derive linearized transient stability constraints outside the OPF calculation to not further complicate the OPF formulation. In [17], time-domain simulations are combined with pre-assessment contingency filtering and a fast re-dispatch estimation to reduce the computational burden of the stability assessment.

3.1.2 Load Shedding

When referring to load shedding most commonly it will be associated with frequency regulation such as under frequency load shedding to prevent a power system from collapse due to generation deficit. However, load shedding can also be used to improve transient stability of power systems, e.g. reduce the loading of generators by reducing the demand. That can be again boiled down to the power-angle relationship in Fig. 1, i.e. the reduced active power set point of the generator implies a reduction of the rotor angle and thus an increased stability margin. The authors of [18] have proposed a risk-based coordination of generation rescheduling and load shedding to improve transient stability. If the generation rescheduling cannot resolve the issue, load shedding is added to ensure that the system is within the defined security boundaries.

3.1.3 Reduction of System Reactances

Transmission networks are mainly determined by their inductive series reactances which have distinct impact on the transient stability. The power transfer capacity scales inversely proportional with the transmission reactance. The transfer capability in pre-fault conditions can be increased by reducing the series reactances of the network. A reduction of the system reactances can be achieved by adding parallel transmission lines and/or use of transformers with low leakage reactances [13]. Since this two techniques for reducing the system reactances are rather expensive, other techniques as fixed or variable series compensation based on FACTS are used (refer to sections 3.1.5 and 3.2.6).

3.1.4 Upgrade of System Voltage

The transfer capacity increases proportionally to the square of the system voltage. An increase in system voltage increases the difference between the initial rotor angle and critical clearing angle allowing the generator rotating through a large angle deviation before reaching the critical clearing angle. Moreover, the deceleration area A_2 is increased. It is obvious that increasing the system voltage is not applicable to a large existing power system as the components of the power system are designed for a specific voltage level and must be replaced before increasing the voltage level. Therefore, increasing the system voltage is only applicable to a very limited extend.

3.1.5 Variable Series Compensation

Thyristor-controlled series capacitor (TCSC) and static synchronous series compensator (SSSC) are capable to act on the power system in a serial manner, contrary to shunt devices. Variable series devices can be used in preventive as well as in emergency control. For emergency control, please refer to section 3.2.6.

The circuit diagram of a TCSC is shown in Fig. 2. It consists of a fixed series capacitor C_2 and a capacitor C_1 in parallel with an inductor L. The thyristor controls the total reactance of the circuit according to (2), where ω_e is the electrical angular frequency and α the firing angle of the thyristor control.

$$X_{TCSC} = \frac{1}{-\omega_e C_1 + \frac{2\pi - 2\alpha + \sin(2\alpha)}{\omega_e L \pi}} \tag{2}$$

Instead of line reinforcement or installation of additional lines, TCSCs offer a strong alternative to improve transient stability by optimizing the transmission impedance [19]. The TCSC reduces the effective series reactance X_{Line} and, thus, reduces the angular separation with the power transfer being constant.

A similar effect can be achieved by use of a SSSC. The circuit diagram and respective vector diagram are shown in Fig. 3. The SSSC injects a voltage, which is variable in magnitude and perpendicular to the line current. The angle of the injected voltage can be $\pm 90°$ with

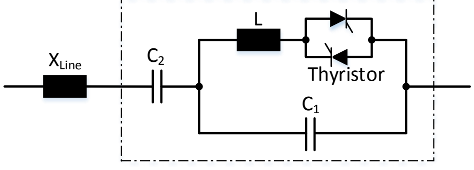


Fig. 2: Circuit diagram of a TCSC

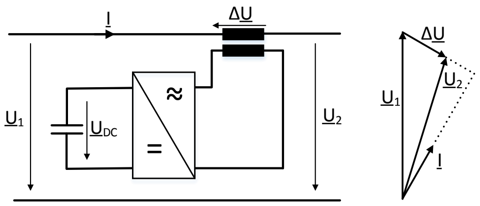


Fig. 3: Circuit and vector diagram of a SSSC

respect to the line current and either emulate an inductive or capacitive reactance [20].

3.2 Emergency Transient Stability Control

3.2.1 Fast Excitation System

A significant improvement of transient stability can be achieved with fast responding excitation systems of SGs by increasing the field current to increase the internal machine voltage and, hence, to evacuate more electrical power during the fault which reduces the acceleration area and leads to an increased CCT.

High speed excitation systems are not very effective for bolted three-phase faults at the generator terminals since the voltage drops to zero. No active power can be evacuated. However, it is very effective for faults occurring further away from the generator, where the voltage at the generator bus is greater than zero [21].

Another technique is a discontinuous excitation control which is referred to as transient stability excitation control where the terminal voltage is kept near the maximum permissible value over the entire positive swing of the rotor angle and returns to normal operation mode after the first swing. The use of fast excitation systems may compromise the damping of local plant oscillations which requires the excitation system to be supplemented with a power system stabilizer (PSS) [13].

In [22–24], the authors introduce non-linear excitation controllers. The controllers are designed robustly, being capable to operate over a wide range of operating conditions. The simulation results show enhanced performance under transient conditions and also improved small signal stability through increased damping of oscillations after the disturbance.

The authors of [22] propose a multi-variable nonlinear controller which takes into account the dynamics of the automatic voltage and speed regulators to achieve simultaneous enhancement of rotor angle stability and post-fault regulation of the terminal voltage. The authors claim that the performance of the control technique is independent from the operation point of the generator and that it can be applied to generators in any power system.

The authors of [23] propose a linear controller which provides an acceptable performance over a wider operating region as conventional controllers. Information about the nonlinearities of the power system are explicitly included in the design of the controller by using the Cauchy remainder of the Taylor series expansion. However, the design of the controller strongly relies on information of the specific dynamic behaviour of the actual power system.

The authors of [24] propose an partial feedback linearization controller for multi-machine systems by including the speed deviation of SGs as an output function. The proposed technique shows superior behaviour over controllers with exact feedback linearization due to faster settling time after disturbances and reduced oscillations.

3.2.2 Braking Resistor

The concept to use a braking resistor to enhance transient stability can be seen from a similar perspective as fast valving (refer to section 3.2.3) with the difference that it acts on the electrical power instead of the mechanical power. An artificial electrical load is applied during transient disturbance to increase the electrical power and to re-establish the equilibrium, or at least minimize the difference, between mechanical and electrical power.

In [25,26], the authors propose two variants of braking resistor, one with a thyristor rectifier and one with a diode rectifier and chopper. A fuzzy logic controlled braking resistor was proposed in [27]. However, for the practical application of braking resistors careful considerations have to be made regarding installation costs, torsional stress on the shaft and other additional adverse effects which may arise.

3.2.3 Fast Valving

Fast valving of the turbine is an effective technique to improve transient stability by rapidly reducing the mechanical power during the fault [13]. According to [28], the concept of fast valving was introduced for the first time in 1925. During faults, the electrical power drops to a lower value and creates a difference between mechanical and electrical power, leading to an acceleration of the machine. To counteract that imbalance, generators with fast valving capability rapidly lower the mechanical power which is applied to the machine in order to reduce the acceleration power to a minimum. One of the limitations of fast valving is that it can only be applied to thermal units [29].

In [30], fast valving is complemented with a braking resistor and a coordinated control concept of both techniques was introduced. The combined method utilizes the advantages of fast valving and the braking resistor and also overcomes the issues of both techniques when applied separately. For example when faults occur close to the generator terminals, the voltage drops significantly and the breaking resistor cannot be effective until the fault is cleared. However, fast valving can be applied from the very beginning of the fault which allows to effectively control the rotor acceleration during the fault period. Furthermore, the braking resistor only has to share the partial load which reduces duty and heat dissipation.

3.2.4 Generator tripping

Selective tripping of generators for severe contingencies has been used for many years. Various approaches considering very different aspects are found in the literature. Generator tripping based on the energy function, where the kinetic energy of the system is compared to the potential energy, was proposed in [31]. An approach for generator tripping based on rotor angle prediction was proposed by the authors of [32,33]. In [32], the generators to be tripped are determined by a fuzzy-logic controller, whereas a hybrid approach considering look-up tables is used in [33]. The preparation of the look-up tables is done offline by simulation of the power system [34]. The main issues associated to the generator tripping are: Overspeed resulting from tripping of the generator, thermal stress and high torques on the shaft through sudden load change [13].

3.2.5 Variable Shunt Compensation

FACTS with reactive power capability for voltage control at selected points of the power system can contribute to improve the transient stability by increasing the synchronization power flow among the generators [13]. Static var compensator (SVC) and static synchronous compensator (STATCOM) are capable to control the voltage/reactive power at their connection point. Figure 4 shows a typical arrangement of a SVC. It comprises a mechanical reactor and capacitor, a thyristor controlled reactor and capacitor, and a harmonic filter. A standard PI controller for SVCs, which uses the voltage measurement as input to control the reactive power, was introduced in [35].

The circuit diagram of a STATCOM is provided in Fig. 5. The reactive power injection of the STATCOM

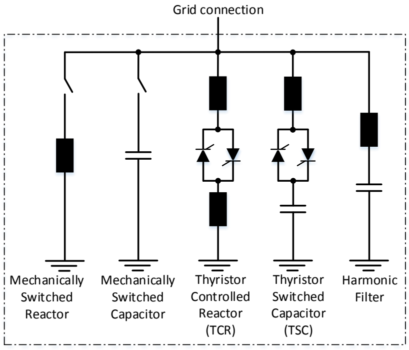


Fig. 4: Circuit diagram of a SVC

is controlled by a pulse-width-modulation (PWM) controller which input is the measured grid voltage at the point of connection.

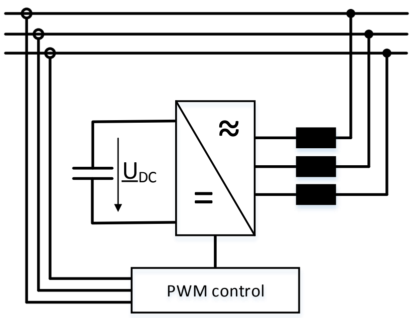


Fig. 5: Circuit diagram of a STATCOM

3.2.6 Variable Series Compensation

zh A wide variety of control concepts for TCSCs for transient conditions are summarized in [36]. The control concepts for TCSCs under disturbance are ranging from linear, non-linear [37–40] to intelligent [41, 42] concepts.

In [37], the authors propose a concept using non-linear model predictive control including the complete set of differential algebraic equations of the system, whereas the Lyapunov energy function is used in the control proposed in [38]. A control concept using remote signals from phasor measurement units (PMUs) was presented in [39]. The authors of [40] propose an adaptive control strategy by adopting immersion and invariant stabilization and sliding-mode observer in the control design.

The intelligent control concept in [41] utilizes the flexibility of artificial neural networks (ANNs) to circumvent the mathematical modelling of the non-linear power system, instead, the non-linear behavior is approximated by the ANN. In [42], the mathematical modelling of the power system is circumvented by use of a fuzzy logic control which is designed for certain grid conditions using engineering expertise about the power system under consideration.

The control concepts for SSSCs can be also categorized in linear [43], non-linear [44] and intelligent [45–47].

A linear proportional control which is sensitive to deviations of the speed of generators is proposed in [43]. The control signal is derived by multiplying the speed deviation from nominal speed with a constant gain value.

The proposed non-linear controller in [44] tracks the generator's angle trajectory to appropriately change the effective post-fault line reactance in order to bring the generator back to a stable operating point and, moreover, to damp rotor oscillations.

In [45], an ANN-based control concept for SSSCs using speed deviations of generators is presented. The authors of [46] propose to use particle swarm optimization to find the optimal parameters of a controller which consists of a gain, a signal washout and a two-stage phase compensation block. A fuzzy logic control using the active power and voltage at the terminals of the SSSC as input for the control is proposed in [47].

3.2.7 Combined Variable Series and Parallel Compensation

In order to achieve full controllability of the series-injected voltage in magnitude and angle, a unified power flow controller is used. An unified power flow controller (UPFC) combines the capabilities of a STATCOM and a SSSC as it can be seen in Fig. 6. Most commonly, inverter 1 is operated at unity power factor, only supplying the active power demand of inverter 2. Due to the supply of active power to inverter 2, it is capable of exchanging also active power with the grid and, therefore, varying the injected voltage $\Delta\underline{U}$ in the full control range shown in Fig. 6. The limitations of the magnitude of the injected voltage are given by the inverter's capacity.

In [48], an approach using an UPFC to maximize the first swing stability by enlarging the deceleration area through reactive power support was introduced. After the first swing, the controller switches to normal linear operation to damp oscillations. A combined control of active and reactive power control for first swing stability improvement using an UPFC was proposed in [49]. A different approach was introduced in [50], where a Lyapunov energy method based control concept was used. Since the difficulties in constructing an analytical energy function have not been overcome, an energy-function-based adaptive recurrent neural network controller was designed. Another intelligent control technique using a neural-network based adaptive controller was introduced in [51]. The controller can be treated as an approximation of the Lyapunov control actions and is robust to uncertainties. In [52], the authors propose a method for optimal placement of UPFCs to decrease implementation costs.

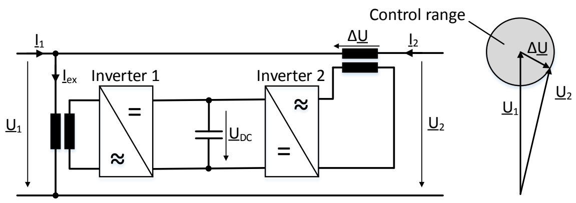


Fig. 6: Circuit diagram of an UPFC

3.2.8 Controlled System Separation

The coordinated separation of the disturbed system into two or more subsystems is a way to prevent a generator or a group of generators from loss of synchronism. The separation concepts use different triggers to initiate the separation process.

In [53], the proposed method is based on on-line voltage waveform measurement and prediction of the phase difference 200 ms ahead. The predicted phase difference is used as a triggering event if a certain limit is exceeded.

A method to determine the optimal point of separation by analyzing the voltage fluctuations in the system was introduced in [54]. The point of separation is determined by the highest voltage magnitude fluctuation and is therefore called out-of-step center. Following this methodology, a separation interface where the system is to be split was derived.

To prevent tripping of out-of-step relays at undesired locations, a blocking scheme by using blinders in the impedance plane for relays was introduced in [55].

The authors of [56] propose an a priori transient stability indicator based on the extended equal area criterion to determine if the islanded power systems remain transiently stable after the network has been split.

The authors of [57] propose an islanding scheme which minimizes the power disruption and power imbalance of the split systems by power flow tracing.

An islanding methodology using constrained spectral clustering is proposed in [58]. The methodology allows to directly determine an islanding solution with minimal power flow disruption for any given number of islands.

3.2.9 High Speed Circuit Breaker, Single-Pole Operation, Auto Re-Closing

Generators are accelerating and picking up kinetic energy during severe faults. The kinetic energy which is picked up by the generator is directly proportional to the fault duration. Therefore, it is desired to clear faults as fast as possible, i.e. the shorter the fault duration the smaller the severity of the disturbance [13,59]. Nowadays, the tripping times of high-speed circuit breakers are around 2 cycles for high voltage and one cycle for low- and medium voltage circuit breakers [60–62]. To achieve this fast clearing times fast overcurrent sensors and dedicated communication equipment are required.

Moreover, it is beneficial to use circuit breakers with independent-pole operation where every phase can be operated separately. That contributes to further transient stability improvement as single-phase to ground faults can be cleared by switching only the pole with the faulty phase instead of switching all three poles, since it allows synchronizing power to flow on the remaining phases. Moreover, the failure of one pole will not affect the operation of the other two poles [21]. However, when using single-pole operation considerations concerning asymmetrical operation of generators have to be made since negative-sequence currents are flowing during the fault. In addition to above techniques, auto re-closing of the breaker can contribute to improve the transient stability by re-establishing the transmission reactance and, thus, increase transmission capacity in post-fault conditions [13,63,64]. The re-closing time has a major impact on the stability and research has been done on determining the optimal time for re-closure of the circuit breaker [65,66]. However, no general rule for the optimal time of re-closure can be defined since many power system properties such as inertia, system configuration and fault location among others are influencing the determination of the optimal re-closure time.

3.2.10 Fault Current Limiter

The application of fault current limiters (FCLs) is very well covered in the literature. Resistive, inductive or combined designs are used to enhance the transient stability during faults. The resistive type is effective in consuming the acceleration energy of generators during faults whereas the inductive type suppresses the voltage drop.

The used FCLs in power systems can roughly be grouped into two categories, namely superconducting

FCLs [67–72] with highly non-linear response to temperature, current and magnetic field variations, and bridge-type FCLs based on solid-state devices [73–76] which are either IGBT or thyristor-controlled.

Superconducting FCLs: The most common configuration of superconducting resistive and inductive FCLs is shown in Fig. 7. FCLs are installed in series of a line. In steady-state, the current I is flowing through the superconductor x_{SC} which has zero resistance. During a fault, when the current exceeds the activation value of the superconductor, the reactance of the superconductor increases instantaneously and causes the current also to flow through the limiting resistor R_{lim} or inductor x_{lim}.

The impact of resistive FCLs on the transient stability behavior is investigated in [68–70, 72]. It was found that the placement of the FCLs and the value of the resistance highly affects the transient stability performance, but generally, a larger resistance showed more robust behavior to changing system parameters.

The authors of [67] investigated the differences between resistive and inductive FCLs. It was found that both types reduce the magnitude of the fault current significantly, but the inductive type showed slightly better performance at damping power oscillations.

A parallel configuration of an inductive FCL with a zinc oxide (ZnO) device and resistor is proposed in [71]. It is shown that the proposed combination of resistive and inductive FCL can significantly improve transient stability by exploiting the voltage drop suppression of the inductive type and the excessive energy consumption of the resistive type.

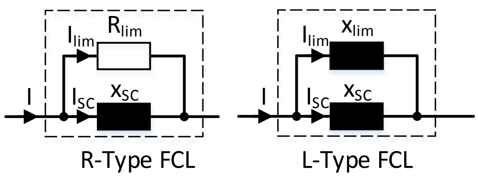


Fig. 7: Most common configuration of superconducting resistive and inductive FCLs

Bridge-type FCLs: bridge-type FCLs utilize actively controlled power electronics to switch the fault current in a limiting branch or opens the circuit to emulate a circuit breaker with the characteristics of the device [77]. Due to the great variety of bridge-type FCL configurations, no figure about standard configurations is shown here.

A method to calculate the optimal resistance of the fault current limiter by finding the resistance value for which the power transfer capability during the fault is equal to the power transfer capability before the fault is proposed in [73]. The authors of [74] propose to use the EAC to calculate the optimal resistance which leads to maximum critical load angle.

In [75], a comparison between a bridge-type and a similar parallel resonance FCL is presented. The results show that the parallel resonance FCL has better performance than the bridge-type FCL for symmetrical and asymmetrical faults.

The authors of [76] propose three non-linear controllers to control a resistive bridge-type FCL. a) a fuzzy logic controller which uses the power and voltage deviation at the point of common coupling (PCC) as input, b) a static non-linear controller which uses the power deviation at the PCC as input, c) an adaptive-network-based fuzzy inference system based controller which uses the voltage deviation at PCC and the speed deviation of the generator as input. The simulation results show only slight differences between the three proposed controllers, therefore, the authors claim that any of the proposed techniques may be chosen to enhance transient stability.

3.2.11 HVDC Transmission Link Control

The number of HVDC links for long-distance transmission of power is continuously increasing. Due to the high controllability of voltage source converters (VSC), using pulse-width-modulation (PWM), in terms of response time and precision, they are very suitable for supporting the AC system by fast and independent control of active and reactive power [78]. The reactive power control usually operates in constant voltage or droop mode. If the converters have LVRT capability, the transient stability can also be enhanced by reactive power provision. When the DC transmission links are operated in constant power mode they do not support the AC system by, e.g. damping oscillations. Hence, it is beneficial to modify the control of the converters in such a way that they support the AC system during disturbances.

A model predictive control (MPC) using on-line measurements collected through a wide-area monitoring system was introduced in [79]. Based on the collected data, a sequence of control actions that maximize a transient stability index over a short time horizon is calculated in every discrete time instant. The used transient stability margin is a combination of an acceleration power, coherency and energy index. The first action of the computed sequence is used as control setting for the HVDC links.

In [80, 81], three control techniques for transient stability improvement by adding supplementary controls to the constant power control of converters are introduced. The DC power flow control signal P_{DC} is the sum of the DC power flow set point P_{DC_0} and the supplementary signal for transient conditions DC_{suppl} as shown in (3).

$$P_{DC} = P_{DC_0} + P_{DC_{suppl}} \tag{3}$$

The three controllers are explained in more detail in the following. Here, the index R and I correspond to rectifier and inverter, respectively. K_P and K_D are the respective proportional and differential gains of the PD controllers.

a) The aim of the first controller is to transfer power from the area where the SGs are accelerating faster to the area where the SGs are slower and, thus, increasing the transient stability by providing synchronization power flow between SGs with different speed. The rotor speeds ω_R and ω_I of the SGs located closest to the inverter and rectifier buses of the HVDC link.

$$\begin{aligned} P_{DC_{suppl}} = K_P(\omega_R - \omega_I) + \\ K_D \cdot \frac{d}{dt}(\omega_R - \omega_I) \end{aligned} \tag{4}$$

b) The second controller's input are the voltage angles φ_{V_R} and φ_{V_I} at both ends of the HVDC link. The voltage angle displacement provides a good image of the mechanical rotor displacement between the generators at either side of the HVDC link. To increase transient stability, the active power flow through the HVDC link is controlled so that the voltage angle is minimized and, hence, the mechanical rotor displacement is decreased.

$$\begin{aligned} P_{DC_{suppl}} = K_P(\varphi_{V_R} - \varphi_{V_I}) + \\ K_D \cdot \frac{d}{dt}(\varphi_{V_R} - \varphi_{V_I}) \end{aligned} \tag{5}$$

c) The third controller receives the inter-area power flow on AC tie-lines which is represented by the sum of all tie-line flows P_{TL_k} with k being the number of tie-lines as input. This control strategy supposes well-defined control areas which are interconnected by HVDC links. The active power flow is modulated according to the power flow between the control areas following (6).

$$\begin{aligned} P_{DC_{suppl}} = K_P \cdot \sum_k P_{TL_k} + \\ K_D \cdot \frac{d}{dt} \sum_k P_{TL_k} \end{aligned} \tag{6}$$

These control concepts are applicable in point-to-point HVDC transmission links, whereas control concepts for multi-terminal HVDC (MT-HVDC) systems are more sophisticated because more factors have to be taken into consideration.

In [82], the authors propose three active power control concepts for MT-HVDC systems based on local and global frequency measurements at the converter buses. Local measurements are used to compare the frequency to the nominal value and control the active power flow according to (4). In order to maintain the required active power balance of the MT-HVDC system, a concept which adds weighting factors to the control signal is proposed. By using global frequency measurements, converters inject a fixed supplementary active power considering the speed of the center of inertia (COI).

A time-optimal control strategy to enhance transient stability by coordinated control of multi-terminal DC grid power injections based on Lyapunov theory is presented in [83].

4 Renewable Energy Source Based techniques

In this section techniques and concepts for transient stability improvement are discussed, which utilize RES-based generators.

4.1 Preventive Transient Stability Control

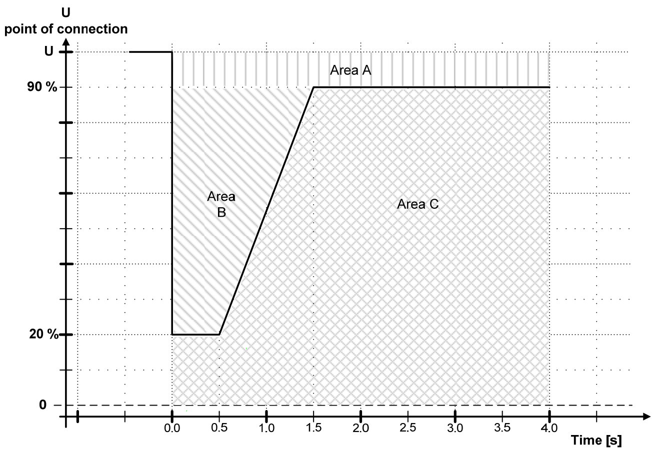
4.1.1 Increased Voltage Setpoint

RES with capability to control reactive power, such as doubly-fed induction generators (DFIGs), full-scale converter-based wind power plants and PVs could be set to operate at a higher voltage setpoint if necessary. However, the increase of voltage setpoints is only possible to a very limited extend due to the constraints set by grid codes. Depending on the location of the RES in the grid, the increased voltage setpoint improves the flow of synchronizing power. In [84], it is shown that the increase of the voltage setpoint of DFIGs from 1 to 1.05 pu in pre-fault conditions can improve transient stability.

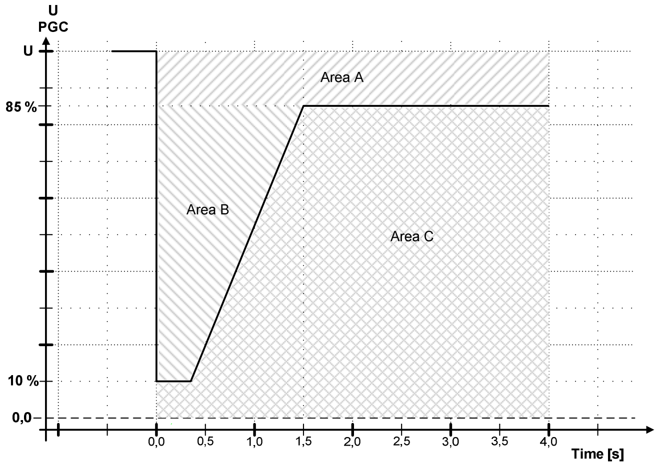
4.2 Emergency Transient Stability Control

4.2.1 Low Voltage Ride-Through

Generally, low voltage ride-through capability of RES has a positive effect on the transient stability of power systems since the disconnection of a large amount of distributed generation would stress the power system even more. Therefore, it is desired that RES remain connected during faults within specified limits. This limits



(a) Wind power plants > 1.5 MW



(b) PV power plants > 1.5 MW

Fig. 8: Energinet's requirements for tolerance of voltage drops for (a) wind power plants and (b) PVs with a power output greater than 1.5 MW. **Area A:** The power plant must stay connected to the network and uphold normal production. **Area B:** The power plant must stay connected to the network provide maximum voltage support. **Area C:** Disconnecting the power plant is allowed. [85,86]

are already defined in many network codes where generation units connected to the grid have to comply with certain LVRT capabilities, e.g. reactive power provision during disturbance. The ENTSO-E network code specifies the requirements for generation units connected to the five synchronous areas in Europe [87,88]. The network code is applicable to all generation units. However, national grid codes even specify particular requirements for wind and PV generation.

The Danish network code for wind and PV power plants with power output above 1.5 MW requires units to stay connected for a certain time during disturbances with respect to voltage and frequency excursions [85, 86]. Generation units with a rated current of 16 Ampere per phase or lower do not have any LVRT requirements [89].

As shown in Fig. 8, the requirements for wind and PV power plants in Denmark are slightly different. The requirements for PVs are more demanding than the requirements for wind power plants as they have to be able to withstand voltage drops down to 10 % of the voltage at the point of connection whereas wind power plants only down to 20 %. Similar requirements apply to wind and PV generation units in Germany and other European countries [90,91].

In addition, advanced control strategies to complement and enhance the LVRT capabilities were developed for DFIGs and full-scale converter wind power plants. These techniques aim at improving the transient behavior of the wind power plants and, thereby, supporting the grid during severe disturbances.

DFIGs are equipped with a crowbar in order to protect the rotor-side converter from overcurrents. The crowbar is inserted once the rotor current exceeds the maximum permissible limit and the rotor-side converter is disconnected. When the crowbar is activated, the DFIG operates like a conventional squirrel-cage induction generator and, therefore, will significantly increase the reactive power consumption [92]. To overcome this problem, the authors of [93] proposed a decoupled-DFIG LVRT strategy to control the DFIG during crowbar operation as induction generator and the grid-side converter as STATCOM. The approach aims at harnessing the natural inertia of the generator and provide reactive power support from the grid-side converter.

Wind turbines with fully-rated converter are completely decoupled from the AC grid and, thus, the converter equipped with dedicated controls can provide transient stability enhancing services.

In [94], an approach to enhance LVRT capability of wind power plants with permanent magnet synchronous generators (PMSM) equipped with fully-rated converter was proposed. During faults, the grid-side converter provides voltage support through reactive power provision. The generator-side converter controls the DC-link voltage by adjusting the active power flow. The resulting surplus of mechanical power delivered from the wind turbine rotor is transformed into rotational energy of the generator rotor, i.e. the rotor accelerates. After the grid voltage is recovered, the additional kinetic energy is released to the grid and the rotor decelerates and returns to normal operation.

4.2.2 Wind Power Plants supplemented with FACTS

Many papers about transient stability improvement by complementing wind power plants with FACTS can be found in the literature. The main reason for that is that the majority of wind turbine designs include induction machines (IM). Because of their nature, wind turbines with directly grid-connected IMs (wind power plants of type one and two) are not able to control the reactive power at their terminals, instead reactive power is consumed from the grid. The reactive power consumption even increases during transient conditions. Due to that shortcoming many publications for transient stability improvement of IM based wind generation using FACTS devices [95–103] are found in the literature. The main aim of all papers is to improve transient stability by reactive power support from FACTS. In particular, SVCs and STATCOMs are used to provide reactive power support during transient conditions due to their good controllability and responsiveness.

4.2.3 Virtual Inertia

The provision of virtual inertia has recently gained more importance as the penetration of converter-based RES is increasing. Virtual inertia is usually referred to frequency stability, but it has also a substantial impact on transient stability. Although the installation of virtual inertia devices does not affect the inertia of SGs, but it may reroute some active power flows in the system and therefore changing the CCT in certain situations. It cannot be guaranteed that virtual inertia has an exclusively positive impact on the overall transient stability of the power system, which provides opportunities for further research.

At times of high RES generation, the available rotational inertia is reduced because conventional synchronous machines are shut down. Virtual inertia can be provided by units which have stored additional energy, either in rotational or chemical form. Wind turbines of type three and four, and battery storages equipped with an 'inertia' control algorithm are suitable for virtual inertia provision.

The authors of [104–106] suggest an implementation of virtual inertia control of DFIG wind turbines via a derivative controller which uses the frequency as an input signal to modify the active power setpoint of the machine according to the rate of change of frequency (RoCoF).

In [107, 108], the authors propose virtual inertia provision by adding a supplementary derivative control signal to the grid-side converter of type 4 (type D) wind turbines. The supplementary control signal changes the active power setpoint of the grid-side converter by adding an active power contribution which depends on the deviation of the system frequency.

A general overview about virtual inertia of wind power plants was recently published in [109].

Approaches to provide virtual inertia with PV plants have been introduced in [110–113]. They utilize the DC capacitor as an energy source to provide additional power or even include an energy storage system in the DC circuit to increase the amount of energy to be released during virtual inertia provision.

A novel innovative approach to provide virtual inertia by using electric vehicles (EV) was proposed in [114] and experimentally validated in [115]. The analysis was carried out considering the technical constraints imposed by IEC61851 which states the general requirements for EV charging systems. Virtual inertia provision is achieved by implementation of a droop control which modulates the current of the battery system depending on the RoCoF.

5 Discussion of the Qualitative Comparison

This section presents a qualitative comparison of transient stability improvement techniques to highlight the strengths and weaknesses, and to indicate an expected future trend. A quantitative comparison depends highly on the selected network and specifically analyzed use cases and, therefore, it is not suitable for the purpose of this paper.

Table 1 and 2 present a qualitative comparison of the preventive and emergency control techniques, respectively.The following aspects are evaluated: Installation need of an additional physical device, investment costs and effectiveness in terms of overall system impact. Moreover, the most important considerations of each technique are highlighted and an expected future trend is indicated. For improved visualization, Fig. 9 shows the Kiviat diagrams for preventive and selected emergency improvement techniques that are considered important in the future. The larger the covered area of an improvement technique, the higher is the overall impact of the technique on the power system.

One general observation is that there are more conventional than renewable techniques for transient stability improvement. Due to the transition to renewable-based generation where a growing number of conventional units are being phased-out, new techniques to preserve transient stability including new generation units must be developed for preventive and emergency controls.

Preventive techniques have to be extended by non-disruptive approaches of stability improvement based

Table 1: Qualitative comparison of **preventive** improvement techniques

	Conventional					Renewable
	Re-Dispatch	Load Shedding	Reduction of System Reactances	Upgrade of System Voltage	Variable Series Compensation	Increased Voltage Setpoint
Additional Device	No	No	Yes	No	Yes	No
Investment Costs	Low	Low	High	High	Medium/High	Low
Operational Costs	Medium	High	Low	Low	Low	Low
Effectiveness	High	Medium	Medium	High	Low/Medium	Medium
Notes	Additional costs due to dispatch to more expensive generators.	Last option due to customer interruption.	High investment costs are associated with new lines.	Limited by power system's voltage constraints.	Device design sets limitations for application. Resonance effects to be considered.	Limited by device capability and system's voltage constraints.
Future Trend	Inclusion of renewable generation in re-dispatch procedure.	Other techniques that do not disrupt customers are preferred. Generation located in distribution grids may be shed at the same time.	Distance between generation and load centers is increasing due to far off RES, e.g. off-shore wind parks.	To be considered when designing new grids. Not applicable for existing grids.	Careful cost-benefit evaluation before installation is needed.	Only to be used temporarily in situations with low stability margins.

Table 2: Qualitative comparison of **emergency** improvement techniques

	Conventional											Renewable		
	Fast Excitation System	Braking Resistor	Fast Valving	Generator Tripping	Variable Shunt Compensation	Variable Series Compensation	Combined Series and Parallel Compensation	Controlled System Separation	High Speed Circuit Breaker; Single Pole Operation; Auto Re-Closing	Fault Current Limiter	HVDC Control	LVRT	Converter-based RES	Virtual Inertia
Additional Device	No	Yes	No	No	Yes	Yes	Yes	No	Yes	Yes	No	No	No	Yes
Investment Costs	Low/Medium	Medium/High	Low/Medium	Low	Medium/High	Medium/High	Medium/High	Low	Medium/High	Medium/High	Low	Low	Medium	Medium/High
Operational Costs	Low	Low	Low	Medium	Low	Low	Low	High	Low	Low	Low	Low	Low	Low/Medium
Effectiveness	Medium/High	High	High	High	Medium	Medium	Medium	High	High	Medium	Medium/High	Medium	Medium/High	Medium
Notes	Ineffective for nearby faults. Effective for far faults.	Careful cost-benefit evaluation necessary. Stress on shaft and other adverse effects may arise.	Can be applied to thermal units only. Showed to be effective when combined with braking resistor. Governor upgrade might be needed.	Stress on shaft due to overspeed and sudden load change.	Increases the synchronization power by voltage support at selected nodes.	Control of the effective line reactance during and post fault for improved stability.	Full controllability of series injected voltage in magnitude and angle but expensive equipment.	System separation so that least consumers are disrupted. Difficult dynamic process to determine the location to separate the system.	High speed breakers effectively reduce severity of disturbance. Single-pole operation might be critical due to asymmetrical operation. Difficulties in determining the optimal auto re-closing time.	Superconducting FCLs are sensitive to temperature, current and magnetic field variations whereas bridge-type FCLs include active elements to be controlled.	HVDC links operated in constant power mode do not support AC grid's oscillation damping. Reactive power support at terminals and dedicated active power controls enhance transient stability.	LVRT generally positive as disconnection of large amount of RES stresses power system even more.	Main aim of converter-based RES and STATCOMs is to provide fast responding reactive power support.	Virtual inertia gains more attention with respect to frequency stability, however, virtual inertia also influences the transient stability.
Future Trend	Will stay part of future transient stability improvement, but fewer units may be online because of the substitution due to RES.	Decreased use is foreseen due to transition to RES. Other techniques for RES-based generation to be used and/or developed.	Due to the limited applicability and transition to RES, decreased use is foreseen in the future.	Will still be one of the options for severe grid disturbances to prevent pole-slipping causing even more severe grid disturbances.	Less need for additional shunt devices as newly integrated converter-based RES could provide voltage support.	The foreseen increased number of HVDC connections will allow to control active power flow (and so voltage angle) to certain extend. Less need for serial compensation.	Decreased use of these rather expensive devices due to other emerging possibilities involving converter-based RES units.	Will still be part of grid defense strategy for severe disturbances to save the overall system from large blackouts.	Dedicated communication equipment is foreseen to improve speed and reliability of high speed breakers. Research on effects of asymmetrical single-pole operation and auto re-closing of breakers on RES-based generation is needed.	Fault currents in future power systems might decrease due to current-limited devices, such as converters. Might result also in lower need for fault current limiters.	Higher need for dedicated HVDC control with increasing number of HVDC lines. AC system needs to be supported in terms of voltage support and oscillation damping.	LVRT capabilities will be crucial in future systems with highly decentralized generation to avoid auto-disconnection of large portions of generation.	Trend towards WPP designs with reactive power capability (DFIG & fully-rated converter WPPs) decrease need for supplementary STATCOM.	The relation of transient stability and virtual inertia must be investigated as the implementation of virtual inertia for frequency control will also affect the transient behavior.

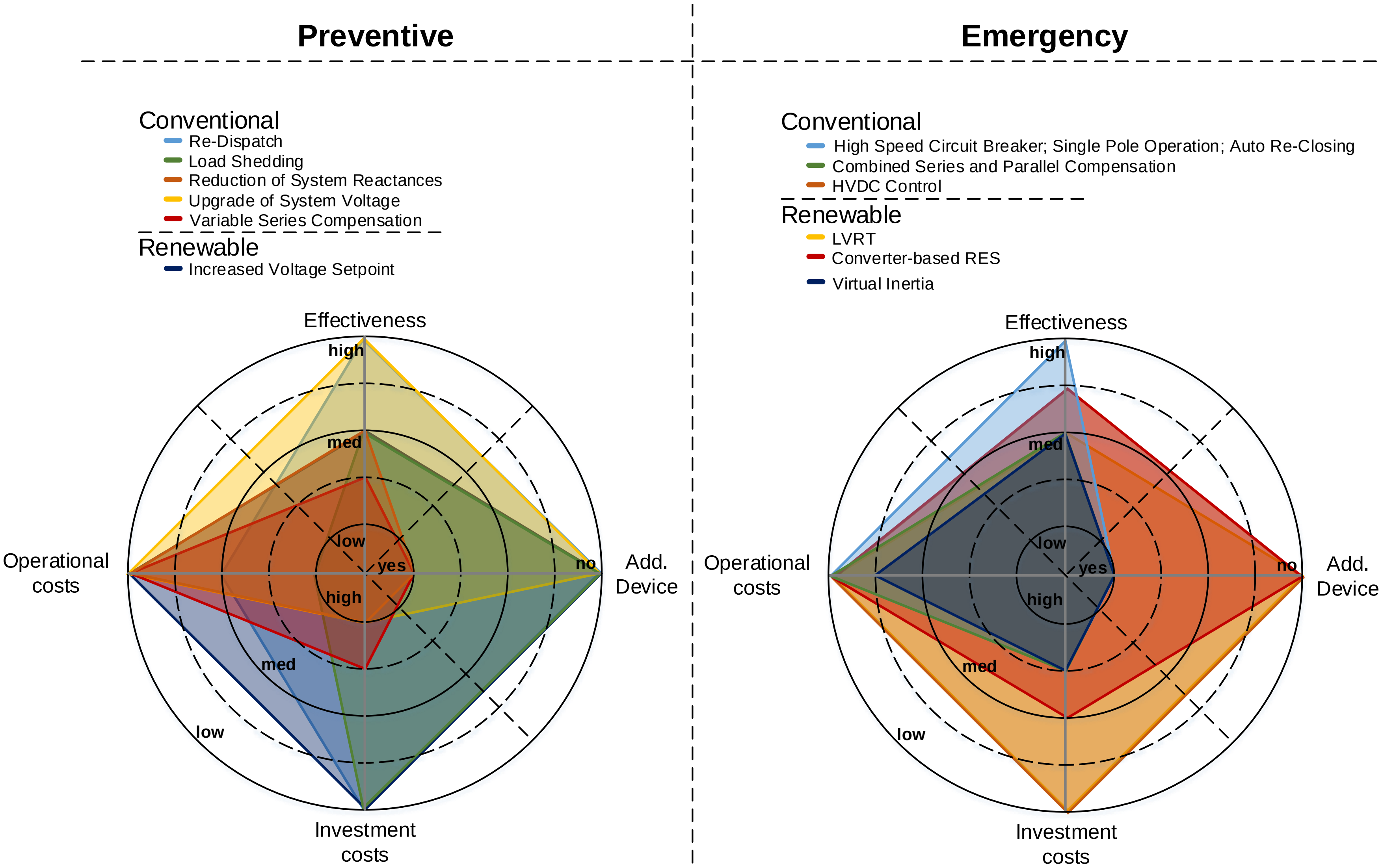


Fig. 9: Kiviat diagrams of preventive and emergency improvement techniques

on RES units. techniques that need low investments are preferred, hence, future research shall focus on inclusion of RES units in existing preventive control strategies. Re-dispatch procedures shall include RES units to relieve SGs if they are operated close to their stability limits. Conventional techniques that are constrained by grid limitations must be carefully considered at the grid planning stage to minimize subsequent investment costs, while preserving stability and a high reliability of electricity supply.

Conventional emergency techniques, such as fast excitation systems, generator tripping, high-speed breakers and controlled system operation will remain an important part of transient stability improvement. The use of braking resistors and fast valving is foreseen to decrease due to their limited application possibilities. The need for shunt and series compensation devices will decrease as the increase of converter-based units pose opportunities for distributed voltage control, and thereby, enhance stability. The importance of dedicated control of HVDC lines to support the AC system will increase with the expansion of HVDC technology. LVRT is already part of most grid codes as it is highly important to preserve stability whereas the (less frequent) opposite case of HVRT is not always thoroughly defined in the grid codes. Temporary high voltages could emerge in situations of sudden load drops and cause a large portion of RES units to disconnect. A discussion about HVRT and an evaluation of the need to include it into grid codes must be started. Virtual inertia is currently heavily discussed with respect to frequency control, but the impact of virtual inertia on the transient stability behavior has not been sufficiently investigated. That aspect is an unexplored area that definitely needs attention to enable the transition to future low inertia systems.

6 Conclusion and Outlook

The paper presented an overview of techniques to improve the transient stability of power systems. The techniques are categorized into two main groups, namely conventional and RES-based. It is distinguished between techniques applying preventive or emergency controls. A qualitative comparison of the techniques including an expected future trend is presented.

There are various conventional preventive techniques, such as re-dispatch of generators or series compensation which are extensively used in practice. Other conventional preventive techniques, such as increase of system voltage and minimization of system reactances are only applicable very limited due to technical and economic constraints.

There is only limited literature on preventive transient stability control using RES. One method was discussed, which temporarily increases the voltage setpoint in order to enhance the maximum power transfer capability. Further research is needed to develop new techniques for preventive transient stability improvement including RES, e.g. RES-based units need to be considered in existing preventive control strategies. A possibility could be to combine RES units with a storage and through coordinated control, e.g. temporary re-dispatch, a certain transient stability margin could be achieved.

A wide variety of conventional emergency techniques were found in the literature. A great share of them aims at voltage support during fault conditions in order to either increase the electrical power which is evacuated from the generator or to increase the synchronizing power flow between the generators. Other techniques are aiming at reducing the fault severity by means of fast fault clearing using high speed breakers with dedicated communication equipment, including single-pole operation and auto re-closing of breakers. Two widely used techniques are selective generator tripping to avoid instability and controlled system separation. Both techniques aim at saving the power system from widespread outage by shedding of critical units, sometimes in combination with load shedding to avoid frequency problems, or splitting the system into functioning subsystems. The control of HVDC links in transmission systems represents a possibility to significantly improve the transient stability of large power systems due to their good controllability. Dedicated HVDC control is seen as an approach with high potential for transient stability improvement of large interconnected systems because HVDC links are usually designed to transmit large powers over long distances and they also have a fast response time.

Regarding transient stability emergency control involving RES, two main categories can be distinguished. A lot of research was carried out aiming to improve LVRT behavior of wind power plants and PVs in order to support the system during disturbances. The research focus on LVRT behavior of RES is owed by the fact that in recent years grid codes also included LVRT capabilities of renewable sources due to their increasing share in the generation portfolio. In addition, research concerning HVRT capabilities need to be carried out to understand if these events would compromise the reliability of the system due to disconnection of large portions of distributed generation. The second area which is seen as promising with respect to transient stability emergency control by RES is the provision of virtual inertia. Virtual inertia is mainly referred to frequency stability, but there is also a significant potential seen for the improvement of transient stability. However, to the best of our knowledge, there has no research been done about how virtual inertia affects transient stability, e.g. the type and location of the devices used for virtual inertia provision.

The qualitative comparison showed that a mix of conventional and RES-based techniques will be needed in a future power system based on diverse and distributed RES. Conventional techniques need to be further developed and new techniques for RES-based generators need to be investigated.

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